



6th CIRP International Conference on High Performance Cutting, HPC2014

Machinability of powder metallurgy steels using PcBN inserts

Rachid M'Saoubi^{a*}, Tobias Czotscher^{a,b}, Olof Andersson^c, Daniel Meyer^b^a R&D Material and Technology Development Seco Tools AB, Björnbacksvägen 02, SE-73782 Fagersta, Sweden^b Foundation Institute of Materials Science (IWT), Badgasteiner Str. 3, D-28359 Bremen, Germany^c Höganäs AB, Bruksgatan 35, SE-263 83 Höganäs* Corresponding author. Tel.: +46 223 406 68; fax: +46 223 718 60. E-mail address: Rachid.Msaoubi@secotools.com

Abstract

Primary manufacturing of steels by powder metallurgy (PM) is of increasing interest for a wide range of industrial applications. Especially in automotive parts and tools, PM materials are utilized, as they show advantageous behavior regarding chemical, mechanical and functional properties as well as resource efficiency. Consequently, machining of these materials is an emerging topic for both, industry and science. This paper addresses the machinability of PM steels. Two PM high speed steels (HSS) were characterized and machined varying the machining parameters and edge preparation (PcBN inserts) in longitudinal and orthogonal hard turning. Furthermore, the influence of manganese sulfides (MnS) in the PM material was analyzed by comparing experiments applying alloys with defined content of MnS. Besides tool life and achievable surface roughness, the surface integrity was assessed. The results reveal that the amount and shape of carbides as well as the porosity of the PM steels play an important role in the wear mechanism when machining this kind of materials. As expected, addition of MnS leads to a decrease of cutting forces and allows for significantly higher tool life. The influence of machining parameters and the tool edge geometry is discussed. Based on the results, suitable cutting conditions for machining of PM steels can be derived.

© 2014 Published by Elsevier B.V. Open access under [CC BY-NC-ND license](https://creativecommons.org/licenses/by-nc-nd/4.0/).

Selection and peer-review under responsibility of the International Scientific Committee of the 6th CIRP International Conference on High Performance Cutting

Keywords: Machinability, Cutting, Steel, PM Steel

1. Introduction

For several industrial products, the application of powder metallurgical (PM) steels is a promising approach, as the materials feature several advantageous properties. High mechanical strength, wear resistance, and the possibility of near net shape manufacturing [1] led to the increasing relevance of PM steels in the automotive sector or tool manufacturing [2].

The mechanical properties of PM steels, which allow for high functional performance of the components, based on the combination of carbides embedded in a hard matrix [3] affect the machinability considerably. Thus, machining of powder metallurgical high speed steel alloys requires sophisticated machining processes [4 - 6]. For cutting operations, high-performance cutting tool materials such as cemented carbides, high alloyed tool steels, and polycrystalline cubic boron nitride (PcBN) have to be applied [7]. Especially PcBN tools are of increasing interest in this field of machining

applications. The synthetically produced cutting tools show favorable performance like high strength, good thermal conductivity, and heat resistance up to 1500 °C [8]. Furthermore, these inserts are chemically inert against iron and its alloys, which make them a suitable option for high-performance cutting of PM steels [9].

There are many factors influencing the machinability of PM steels in a negative or positive way. The porosity determines mechanical properties and deteriorates the machinability compared to wrought steels [10]. Furthermore, the material microstructure, whether heterogeneous or homogeneous, influences the requirements regarding the cutting process [11, 12]. One way to improve the machinability of hard-to-cut materials is the addition of MnS, which have been described to facilitate machining [13]. However, the large variety of different compositions of powder metallurgical steels restrains the identification of certain outlines and general machining advices [7].

Hence, the main focus of the investigations presented in this paper is to analyze the effects of defined variations of the materials composition on the machinability and the surface integrity.

2. Experimental Setup

Two different PM high speed steels were pressed, sintered, and subsequently analyzed regarding their chemical composition (Table 1). Additionally, samples made of the same materials with 1 wt% of manganese sulfide (MnS) additive were sintered to allow for investigation of the effects of the content of sulfides on machinability. The geometry of the workpieces was ring-shaped with an outer diameter of 35 mm and an inner diameter of 25 mm. The height of the samples was 25 mm. The hardness of the workpieces varied according to the chemical composition within a range of 550 to 690 HV0.1.

Table 1: Composition of work materials

Material	Composition in wt%						
	C	Mn	Si	Cr	V	W	Mo
M2	0.83	0.27	0.32	3.13	1.97	5.12	5.00
OB1	1.50	-	0.50	16.00	1.00	1.50	1.50

Machining experiments with varied edge preparation of PcBN inserts and cutting parameters have been performed in longitudinal ($v_c = 150, 200, 250$ m/min; $f = 0.1$ mm/rev and $a_p = 0.1$ mm) and orthogonal ($v_c = 150, 200, 250$ m/min; $f = 0.050, 0.075, 0.100$ mm/rev and $a_p = 1.75$ mm) hard turning using a Swedturn 300 CNC lathe. For both processes, the cutting tools consisted of PcBN Seco grade CBN200. The effect of the tool geometry was considered to reveal the wear mechanisms and to identify the decisive factors allowing for high performance cutting of PM steels. Tool geometry was varied regarding the chamfer angle ($\gamma_f = 15, 20, 30^\circ$) and edge radius ($r_\beta = 10, 25, 40$ μ m). All experiments were run under dry conditions.

During the orthogonal and longitudinal turning experiments, feed rate, cutting speed, and insert geometry were varied. Tool wear tests were performed in longitudinal turning and tool wear was measured at regular path length intervals using a toolmaker microscope. The tool life criterion was, either maximum flank wear $VB_{max} = 0.2$ mm or crater depth of $KT = 0.1$ mm. The forces were measured using a standard dynamometer and tool temperature field was determined using an IR-CCD based technique. Details about temperature measurement method are described in earlier investigation [14].

The surface topography of the machined surface and the inserts were characterized using an Alicona Infinite Focus 3D optical microscope. Moreover, post-cutting observations of the wear scars on the inserts were done using a high resolution scanning electron microscope FEG-SEM LEO Ultra 55 together with energy-dispersive X-ray spectroscopy (EDX) measurements.

3. Results and Discussion

3.1. Longitudinal Turning

The results of the tool wear test in longitudinal turning (Fig. 1) indicate higher tool life when cutting the workpiece material M2 compared to OB1 independently from the content of MnS.

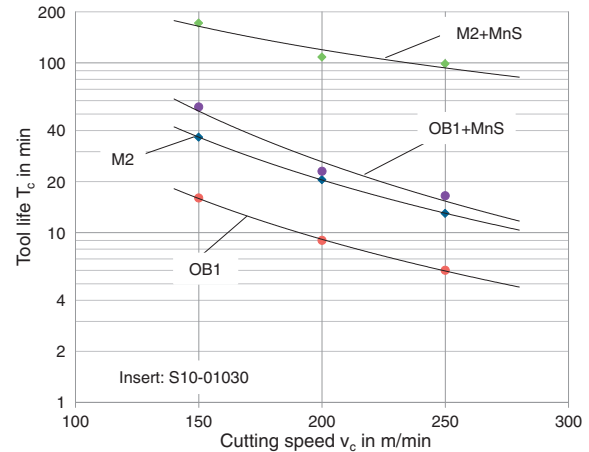


Fig. 1: Tool wear test with insert S10-01030 (chamfer angle $\gamma_f = 30^\circ$, edge radius $r_\beta = 10$ μ m)

Independent from the tool geometry, higher wear rates were caused by the OB1 material as shown in Fig. 2 comparing typical SEM views of the worn cutting edges of identical inserts (chamfer angle $\gamma_f = 15^\circ$, edge radius $r_\beta = 10$ μ m) after 25 m path length. The figure also indicates a built-up-edge generated in the cutting experiments using OB1 as a workpiece material.

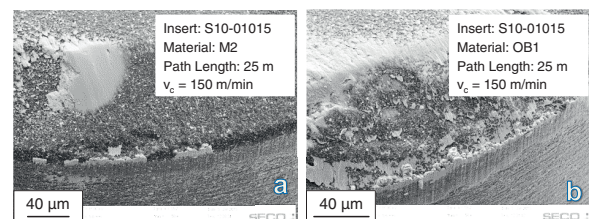


Fig. 2: SEM measurements comparing cutting inserts (chamfer angle $\gamma_f = 15^\circ$, edge radius $r_\beta = 10$ μ m) after 25 m path length in a) M2 and b) OB1

A significant influence on tool wear was obtained for the workpiece materials with increased amount of manganese sulfides resulting in up to a three-fold increase in tool life. An increase of cutting speed has an expected negative effect on the tool life. No significant influence of the insert geometry on the wear behavior has been observed in the context of this study. The wear behavior of inserts with a edge radius of $r_\beta = 10$ μ m and a chamfer angle of $\gamma_f = 30^\circ$ (same tool geometry as in Fig. 1) applied at the highest investigated cutting speeds is shown in Fig. 3 for the end of the experiments (tool life criterion achieved).

Distinct crater and flank wear patterns were observed for all inserts. The formation of a distinct layer of MnS on top of the crater of the inserts was observed when machining the PM variants containing MnS additives. On the other hand, the presence of fine grooves, typical of abrasive wear on the flank, and adhesion of the work material were observed on the inserts machining the standard PM variants.

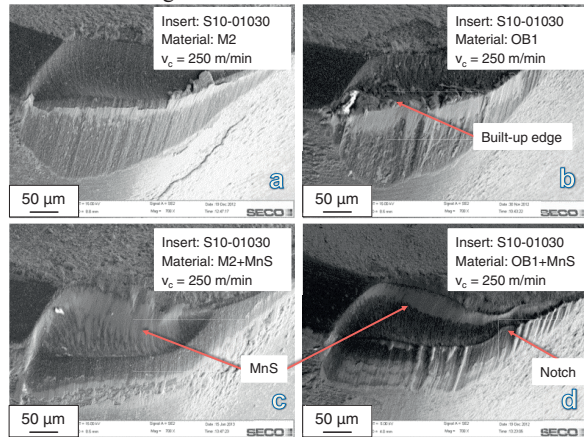


Fig. 3 Wear on worn tools ($v_c = 250$ m/min, chamfer angle $\gamma_f = 30^\circ$, edge radius $r_\beta = 10$ μ m) cut a) M2, b) OB1, c) M2 MnS, and d) OB1 MnS

Comparing the summarizing results of the crater wear analysis at the rake face (presented in Table 2 and Table 3) with the tool life time tests (defined by the wear of the flank face), identical wear behavior can be obtained. The highest crater and largest amount of volume removed over path length are measured on inserts used to cut OB1, whereas M2 with manganese sulfides causes the lowest crater.

Table 2: Crater wear analysis at $v_c = 150$ m/min, chamfer angle $\gamma_f = 30^\circ$, edge radius $r_\beta = 10$ μ m

Material	Path length l_c [m]	Crater depth KT [μ m]	Crater ratio KT' [μ m/m]	Crater volume V [μ m ³]	Volume ratio V' [μ m ³ /m ³]
M2	5800	36.4	$17.3 \cdot 10^{-3}$	533393	$9.2 \cdot 10^9$
OB1	2900	55.0	$21.8 \cdot 10^{-3}$	678323	$23.4 \cdot 10^9$
M2+MnS	10875	20.1	$2.9 \cdot 10^{-3}$	271873	$2.5 \cdot 10^9$
OB1+MnS	8700	50.8	$9.6 \cdot 10^{-3}$	677602	$7.8 \cdot 10^9$

Table 3: Crater wear analysis at $v_c = 250$ m/min, chamfer angle $\gamma_f = 30^\circ$, edge radius $r_\beta = 10$ μ m

Material	Path length l_c [m]	Crater depth KT [μ m]	Crater ratio KT' [μ m/m]	Crater volume V [μ m ³]	Volume ratio V' [μ m ³ /m ³]
M2	3625	44.6	$12.3 \cdot 10^{-3}$	488108	$13.5 \cdot 10^9$
OB1	1450	41.6	$28.7 \cdot 10^{-3}$	478849	$33.0 \cdot 10^9$
M2+MnS	18126	67.0	$3.7 \cdot 10^{-3}$	995374	$5.5 \cdot 10^9$
OB1+MnS	5075	48.6	$9.6 \cdot 10^{-3}$	649638	$12.8 \cdot 10^9$

The corresponding surface topography resulting from the cutting experiments with varied cutting speeds was measured

as shown in Fig. 4 and summarized in Table 4. The results clearly indicate that the best surface finish can be achieved using M2 and OB1+MnS workmaterials, whereas the worst surface finish is measured using OB1. The content of MnS seems to have a slightly negative effect on surface finish for M2. In contrast, manganese sulfides in OB1 appear to improve the surface roughness.

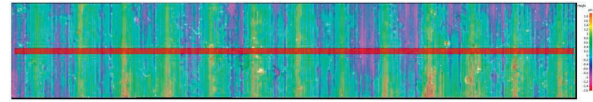


Fig. 4: Machined surface of M2 - measured with Alicona

Table 4: Surface finish of all materials cut by S10-01030 (chamfer angle $\gamma_f = 30^\circ$, edge radius $r_\beta = 10$ μ m) at different speeds

	M2		OB1		M2+MnS		OB1+MnS	
v_c [m/min]	150	250	150	250	150	250	150	250
Ra	0.36	0.46	0.54	0.82	0.58	0.54	0.30	0.38
Rz	1.75	2.19	3.07	4.10	2.76	2.60	1.71	1.94
Sa	0.35	0.45	0.49	0.81	0.62	0.54	0.31	0.39
Sz	3.38	4.07	7.41	10.16	6.51	4.41	7.30	3.92

Higher cutting speeds and even the increasing crater depth have a positive influence on surface finish.

A closer SEM examination of the machined surface of M2 and OB1 (Fig. 5) reveals that the surface of M2 is somewhat smoother, whereas the surface of OB1 shows the presence of cavities and cracks. The machined surfaces from OB1 with MnS reveal comparably small cracks, whereas larger cracks, cavities and even break outs occur at the surface of OB1 without MnS.

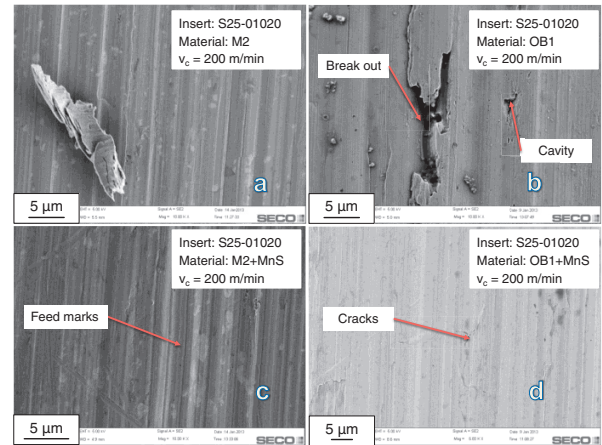


Fig. 5: Machined surface of a) M2, b) OB1, c) M2 MnS, and d) OB1 MnS (chamfer angle $\gamma_f = 20^\circ$, edge radius $r_\beta = 25$ μ m)

A further investigation of the longitudinal cross section of the machined surfaces in Fig. 6 demonstrates that in contrast to OB1, cracks in M2 are observed in the subsurface but do not emerge from the surface of the deformed top layer.

The forces in longitudinal turning decrease due to the presence of MnS in the microstructure. Fig. 7 and Fig. 8 show

the results from the thrust and feed force measurement at cutting speed $v_c = 200$ m/min and tool geometry (chamfer angle $\gamma_f = 20^\circ$, edge radius $r_\beta = 25$ μm).

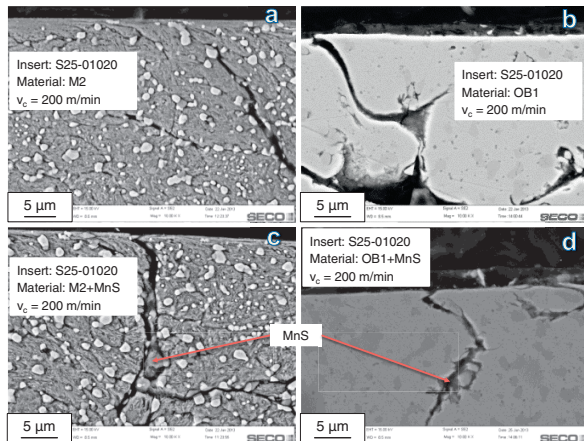


Fig. 6: a) M2, b) OB1, c) M2+MnS, and d) OB1 MnS cross-sections (chamfer angle $\gamma_f = 20^\circ$, edge radius $r_\beta = 25$ μm)

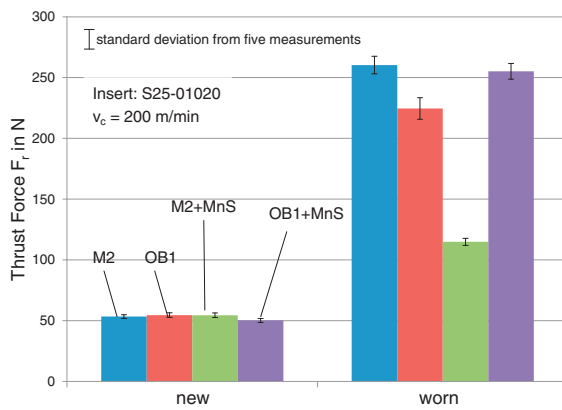


Fig. 7: Measured thrust forces on new and worn tools $v_c = 200$ m/min (chamfer angle $\gamma_f = 20^\circ$, edge radius $r_\beta = 25$ μm)

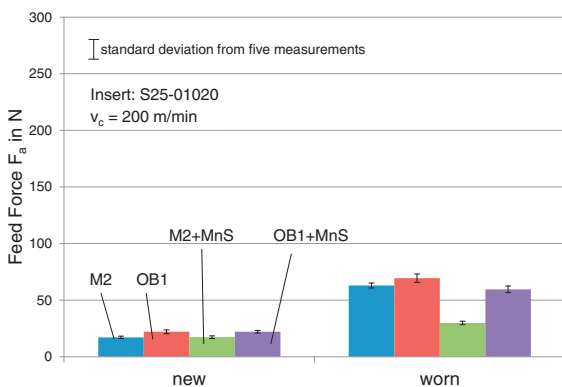


Fig. 8: Measured feed forces on new and worn tools $v_c = 200$ m/min (chamfer angle $\gamma_f = 20^\circ$, edge radius $r_\beta = 25$ μm)

The effect of applying a worn insert ($VB_{\max} = 0.2$ mm) was additionally documented to analyze the stability of the

process. Similar results were observed for different tool geometries. This may be due to the chosen finishing parameters of a cutting depth of $a_p = 0.1$ mm and a feed rate of $f = 0.1$ mm/rev. Higher cutting speeds reduce the thrust forces when cutting materials without additional MnS.

3.2. Orthogonal Turning

Orthogonal turning experiments were performed to assess the influence of feed rate on the cutting forces (Fig. 9 and Fig. 10). The specific cutting force k_c was calculated for all four materials at three different speeds.

The highest cutting and feed forces are measured when machining M2 work material. Moreover, the forces decrease if MnS is added to the PM steels. For the presence of manganese sulfides, the forces decrease more intensively in M2.

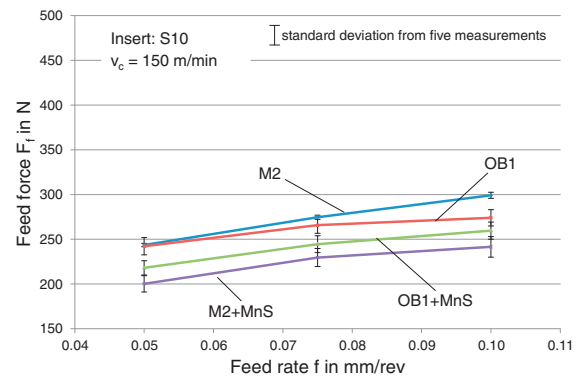


Fig. 9: Feed forces at $v_c = 150$ m/min (chamfer angle $\gamma_f = 10^\circ$)

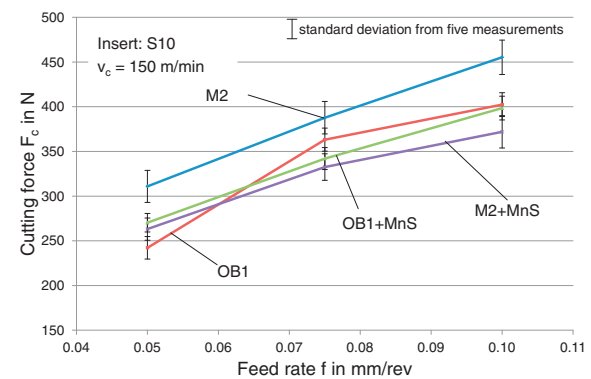


Fig. 10: Cutting forces at $v_c = 150$ m/min (chamfer angle $\gamma_f = 10^\circ$)

The apparent tool-chip friction coefficients were calculated based on the equations by Shaw [15] and are given in Fig. 11. The friction coefficients are almost the same for all investigated materials, which might be due to the chosen finishing parameters. The friction coefficient decreases with higher feed rates. Although it has been pointed out that manganese sulfides have a "lubricating" effect [16], no significant influence of the addition of MnS to the PM steels on the "apparent" tool-chip friction coefficient has been observed in our investigation. It is therefore suggested that the machinability of steels including MnS may be improved e.g.

by the prevention of adhesion rather than by a reduction of friction at the tool-chip contact.

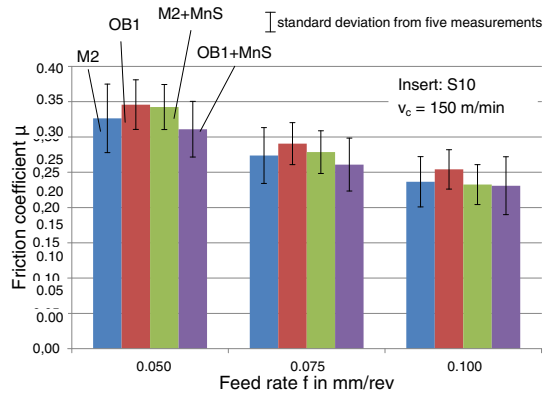


Fig. 11: Calculated friction coefficients at $v_c = 150$ m/min (chamfer angle $\gamma_f = 10^\circ$)

The analysis of the specific cutting forces (Fig. 12) reveals the highest values for the PM steels without an additional amount of MnS. A decrease of k_c is apparently achieved by the presence of manganese sulfides. This effect is independent from the applied cutting speed, as in Fig. 13 similar relationships occur. In general, the specific cutting forces decrease with higher cutting speeds.

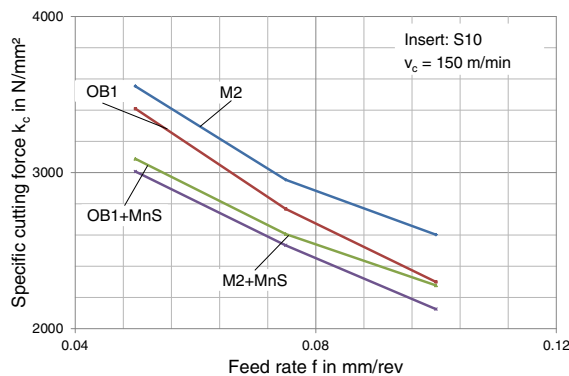


Fig. 12: Specific cutting force at $v_c = 150$ m/min (chamfer angle $\gamma_f = 10^\circ$)

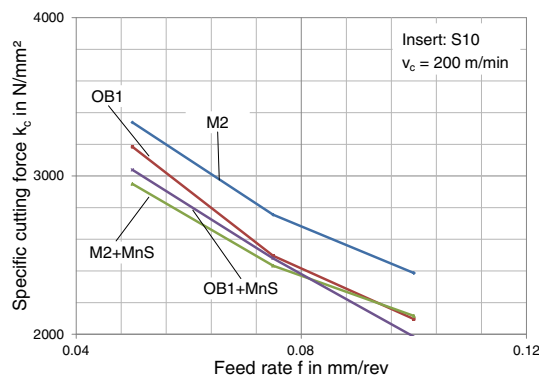


Fig. 13: Specific cutting force at $v_c = 200$ m/min (chamfer angle $\gamma_f = 10^\circ$)

Temperature measurements were performed by thermal imaging to analyze the thermal loads during hard turning of PM steels with varied chemical composition. Fig. 14 shows the temperatures in the contact zone for orthogonal turning at $v_c = 200$ m/min. The PcBN-inserts are exposed to high temperatures up to 860°C . The highest maximum temperatures (mean value of 30 thermal images) occur in cutting experiments using M2 workpiece material ($T_{M2} = 860 \pm 6^\circ\text{C}$). For OB1, the temperature is slightly lower ($T_{OB1} = 800 \pm 10^\circ\text{C}$). This result is in good accordance to the specific cutting forces: the highest specific cutting forces are obtained on M2, which leads to higher cutting temperatures. The presence of manganese sulfides has a remarkable effect on the cutting temperatures. For M2, the addition of MnS leads to a decrease of the maximum temperature to $T_{M2+MnS} = 750 \pm 5^\circ\text{C}$. In OB1 with higher amounts of MnS, the maximum temperature is decreased by 15°C to $T_{OB1+MnS} = 785 \pm 9^\circ\text{C}$. As for the tool wear (see Fig. 1), the effect of adding manganese sulfides to the material is more pronounced in M2 than in OB1.

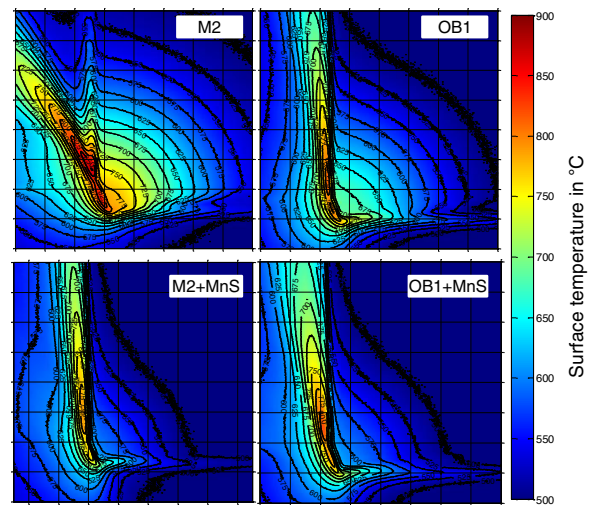


Fig. 14: Thermal measurement PM-PcBN at $v_c = 200$ m/min

4. Summary and Outlook

Tool life, wear behavior, forces and surface integrity of machined powder metallurgy steels using different PcBN inserts have been investigated to analyze the machinability of PM steels. The results confirm that the addition of MnS additives in the PM steels consistently improves tool life of the PcBN inserts and have positive effects on the mechanical and thermal loads during the cutting process. However, the addition of higher amounts of MnS inclusions affects the process differently in M2 and OB1. A higher increase of tool life is observed for PcBN inserts cutting M2+MnS compared to OB1+MnS.

Differences in the microstructure clearly affect the wear rate in cutting of PM steels. M2 consists of small and fine dispersed carbides and shows less porosity. High abrasive wear rates when cutting OB1 as a workpiece material are mainly caused by big and hard chromium carbides, a higher

amount of carbon, and a microstructure with slightly higher porosity.

As expected, cutting materials with higher amount of manganese sulfides results in lower forces. In longitudinal turning and orthogonal turning, higher forces occurred during machining of M2. Regarding the specific cutting force and the cutting temperatures, MnS has a stronger effect in M2 than in OB1.

Concerning surface finish, MnS has a positive effect in OB1 but lowers surface quality in M2. The best surface roughness results are obtained for cutting M2 without MnS and OB1 with MnS.

No significant effect of the tool geometry (chamfer angle and/or edge radius) on wear or forces was observed. Bigger chamfer angle and edge radius seem to slightly affect surface roughness in a positive way.

To allow for high-performance cutting of PM steels, parameters such as cutting speed and feed rate seem to have a more significant influence. Higher feed rates increase the wear rate, forces, and deteriorate surface finish. Higher cutting speeds cause higher flank wear, but improve surface finish. The “lubricating” effect of MnS seems to be more relevant at lower cutting speeds due to relatively prolonged contact times with the cutting edge of the tool. Moreover, the wear mechanism varied for the different PM steels (abrasive wear for M2, abrasive wear and built-up edge for OB1). Manganese sulfides seem to be more efficient in avoiding wear based on built-up edges than reducing abrasive wear. Still, tool life is prolonged by a factor of three to five.

Regarding machinability, OB1 is more difficult to machine compared to M2. An increased productivity and machinability is achieved by free machining aid manganese-sulfide. This enables the use of higher cutting speeds and results in better surface integrity.

Future work will focus on surface integrity issues such as residual stresses and hardness depth profiles. It is expected that the surface integrity of the machined parts can be influenced in a positive way by choosing suitable machining parameters. In combinations with the advantageous machining parameters identified in the present work, this will pave the way to manufacture high quality parts in automotive and tool industry applying the described PM steels. The application of the comparably inexpensive PM steel OB1 was until now considered to be less desirable due to poor machinability. As shown in this work, this may be compensated by the addition of defined amounts of MnS.

Acknowledgments

The authors would like to thank Stefan G. Larsson and Peter Thuresson at Seco Tools AB for helping with the preparation of the tool inserts and metal cutting tests, respectively. Höganäs AB is also acknowledged for supplying the PM work material employed in this study.

References

- [1] Selvakumar N, Mohan Raj A, Narayanasamy R. Experimental investigation on workability and strain hardening behaviour of Fe–C–0.5Mn sintered composites. *Materials and Design* 2012; 41:349–357.
- [2] Lane, MS, Smith P. Developments in sintered valve seat inserts. *Metal Powder Report* 1982; 474–480.
- [3] Nurthen P, Bergman O, Hauer I. Carbide design in wear resistant. *Advances in Powder Metallurgy & Particulate Materials* 2008.
- [4] Bouzakis KD, König W, Vossen K. Use of Powder Metallurgical High Speed Steel in Gear Hobbing and Gear Shaping. *CIRP Annals - Manufacturing Technology* 1982; 31:25–29.
- [5] Karpuschewski B, Knoche H, Hipke M, Beutner. High Performance Gear Hobbing with powder-metallurgical High-Speed-Steel. *Procedia CIRP* 2012; 1:196–201.
- [6] Klink A, Guo YB, Klocke F. Surface Integrity Evolution of Powder Metallurgical Tool Steel by Main Cut and Finishing Trim Cuts in Wire-EDM. *Engineering* 2011; 19:178–183.
- [7] Salak A, Selecká M, Danninger H. Machinability of powder metallurgy steels. 1st ed. Cambridge: Cambridge Int Sci Publishing; 2005.
- [8] Arsecularatne J, Zhang L, Montross C. Wear and tool life of tungsten carbide, PCBN and PCD cutting tools. *Int J of Machine Tools & Manufacture* 2005; 46:482–491.
- [9] Shao F, Liu Z, Wan Y. Diffusion and Oxidation Wear of PCBN Tool based on Thermodynamics. *J of Wuhan University of Technology-Mater* 2010; 265–271.
- [10] Smith G. Drilled hole quality assesment in ferrous PM components. *Powder Metallurgy* 1988; 31:117.
- [11] Danninger H, Spoljaric D, Weiss B. Microstructural features limiting the performance of P/M steels. *Int J Powder Metall* 1997; 43–53.
- [12] Williams J, Deng X, Chawla N. Effect of residual surface stress on the fatigue behavior of a low-alloy powder metallurgy steel. *Int J of Fatigue* 2007; 29:1978–1984.
- [13] Alizadeh E. Factors influencing the machinability of sintered steels. *Powder Metallurgy and Metal Ceramics* 2008; 47:304–315.
- [14] R. M'Saoubi, H. Chandrasekaran. Investigation of the effects of tool micro-geometry and coating on tool temperature during orthogonal turning of quenched and tempered steel, *Int. J. of Mach. Tools and Manuf* 2007; (44)2-3:213–224.
- [15] Shaw MC. *Metal Cutting Principles*. 2nd ed. New York: Oxford University Press; 2005.
- [16] Kishi K, Eda H. The lubrication and deformation mechanism of MnTe, MnS, MnSe and Pb inclusions in various steels during wear and cutting processes. *Wear* 1976; 38/1:29–42.